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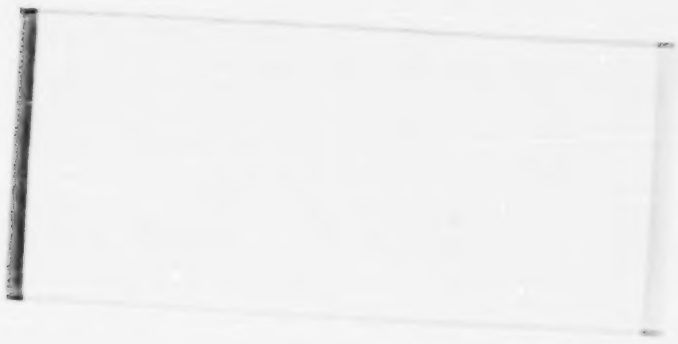

STRENGTH AND STABILITY OF RAILROAD BALLAST SYSTEM

Prepared for

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Un sommaire en français de ce rapport est inclus avant la table des matières.

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17. Abstract

This report covers diverse research work on parameters of ballast not covered by the standard Canadian National Specifications for crushed rock ballast. Hudson's Gradation Modulus A aids in the understanding and reduction of the grading curve to one number and the CN specification to two numbers covering a permissible range. It has been established that increased compaction significantly adds to the shear strength of ballast. A broader gradation produces a higher shear strength than a uniform graded ballast. The Particle Shape Index test correlates well with the Flakiness Index test. An increase in normal load will increase the shear strength.

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17. Résumé

Ce rapport traite de divers travaux de recherche sur les paramètres caractérisant un ballast et qui ne sont pas contenus dans le cahier des charges du Canadien National concernant la pierre dure concassée. En appliquant le module granulométrique A défini par Hudson, on réussit à caractériser la courbe granulométrique d'un échantillon donné au moyen d'un indice unique, et le fuseau granulométrique prescrit par le CN, par deux indices. Le rapport montre qu'un compactage plus intense accroît considérablement la résistance au cisaillement, tandis qu'une granulométrie plus étalée se traduit par une résistance au cisaillement supérieure à celle d'un ballast à granulométrie constante. L'essai sur le coefficient de forme a montré une bonne corrélation avec l'essai sur le coefficient d'écaillage. Enfin, à tout accroissement dans la charge normale correspond un accroissement dans la résistance au cisaillement.

18. Mots-clés	19. Diffusion
Ballastage, résistance au cisaillement, granulométrie, forme des granulats, texture, écaillage	Le Centre de développement des transports dispose d'un nombre limité d'exemplaires.

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EXECUTIVE SUMMARY

The construction industry using aggregates for road beds, asphalt and concrete materials has established a set of tests and standards to obtain suitable materials to meet their needs. Generally, the aggregates used in road beds, concrete and asphalt do not experience the severe service conditions of aggregates used for railway ballast. To meet these different requirements an effort was made to adapt and adopt tests to suit specific ballast needs beyond those specified by standard railway specifications.

A test of an aggregate is significant only if it yields useful information about a significant property or group of properties. Variations in gradation, compaction, shape and surface texture of an aggregate particle may significantly affect the performance of a ballast.

Standard tests prescribed in the CN specification 12-20 for crushed rock ballast do not take into account the most important physical property of a ballast, that being its resistance to shear deformation. The purpose of this investigation was to determine the effect of certain factors, namely gradation, degree of compaction, shape and surface texture on the shear strength of ballast. A series of laboratory tests was performed on four different aggregates to quantify the effect these factors have on shear strength.

Hudson's Gradation modulus A facilitates the application of the grading specification by describing a gradation in terms of one number. Using this method, the CN grading specification can be defined with two numbers: one for the coarse limit and one for the fine limit. Analysis of ballast gradations used currently and in the past shows that the present CN ballast gradation specification is approximately in mid-range for coarseness. Broader gradations produce higher shear strengths than gap graded ballasts, except when using a soft aggregate where the gain is marginal.

Increased ballast compactive effort provides a significant increase in shear strength. Crushed rock ballast achieved the highest resistance to shear when the ballast was highly vibrated and compacted. Uncrushed gravel ballast achieved the highest resistance to shear when the ballast was lightly compacted. Comparison tests with the Flakiness test and the Particle Shape test indicates that the Flakiness test supplies sufficient information to reject unwanted particle shapes.

SOMMAIRE

Afin d'obtenir des matériaux granulaires qui répondent aux conditions d'emploi fixées à l'égard de ceux devant entrer dans les corps de chaussée, les revêtements bitumineux et les bétons routiers, l'industrie concernée a élaboré des normes et mis au point des méthodes d'analyse particulières. Mais ces produits ne subissent pas les contraintes auxquelles sont astreints les granulats utilisés pour le ballastage des voies ferrées. Pour bien définir les contraintes à prendre en compte, il a fallu adapter ou modifier les méthodes d'analyse existantes de manière à parvenir à une définition de tous les paramètres en jeu, y compris ceux non inclus dans les cahiers de charges normalement applicables.

L'essai d'un granulat donné n'est utile que dans la mesure où il aboutit à des données précises sur une ou plusieurs propriétés significatives de celui-ci. On sait que la tenue d'un ballast est fonction de nombreux paramètres, tels que la composition granulométrique, le compactage, la forme et la texture superficielle des granulats.

Les tests normalisés dans le chaier des charges 12-20 du CN concernant les ballasts en pierre dure concassée ne tiennent pas compte du paramètre physique le plus important, à savoir leur résistance à la déformation par cisaillement. La recherche qui a été faite a consisté justement à chiffrer l'influence des paramètres précités sur la résistance au cisaillement. Pour cela, une série de tests ont été effectués en laboratoire sur quatre échantillons de granulats représentatifs.

En appliquant le module granulométrique A défini par Hudson, on réussit à caractériser la courbe granulométrique d'un échantillon donné au moyen d'un indice unique. En développant cette méthode à deux indices, il devient possible de définir le fuseau granulométrique prescrit par le CN au moyen d'un indice indiquant la limite inférieure du fuseau et un autre sa limite supérieure. L'analyse des granulométries généralement utilisées jusqu'ici montre que la granulométrie préconisée par le CN dans son cahier des charges se situe à mi-chemin de l'échelle des granularités en présence. Une granulométrie étalée se traduit par un résistance au cisaillement supérieure à une granulométrie serrée, sauf dans le cas d'un granulat friable où le gain constaté devient marginal.

La résistance au cisaillement augmente de façon importante avec le compactage. Dans le cas d'un ballast en pierre dure concassée, la valeur la plus élevée a été obtenue après vibrage intensif donnant un compactage poussé. Par contre, avec un ballast de gravier, on a mesuré la plus forte résistance au cisaillement après qu'il n'eut été que faiblement compacté. Des essais comparatifs portant sur les coefficients de forme et d'écaillage ont montré que le coefficient d'écaillage est celui qui renseigne le mieux sur les formes de granulats indésireables.

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1. INTRODUCTION

The construction industry using aggregates for road beds, asphalt and concrete materials has established a set of tests and standards to obtain suitable materials to meet their needs. It was only natural that in originally choosing methods of appraisal for the properties of railway ballast, standards used for road and concrete aggregates were adopted for ballast aggregates. Generally, the aggregates used in road beds, concrete and asphalt do not experience the severe service conditions of aggregates used for ballast. To meet these different requirements an effort was made to adapt and adopt tests to suit specific ballast needs beyond that specified by standard railway specifications.

A test of an aggregate is significant only if it yields useful information about a significant property or group of properties. Variations in gradation, compaction, shape and surface texture of an aggregate particle may significantly affect the performance of a ballast. With this in mind it was decided to do tests to determine if gradation, compaction, shape and surface texture have an effect on the shear strength of ballast.

2. PURPOSE

Standard tests prescribed in the CN Specification 12-20 for crushed rock ballast do not take into account the most important physical property of a ballast, that being its resistance to shear deformation. The purpose of this investigation was to determine the effect of certain factors, namely gradation, degree of compaction, shape and surface texture on the shear strength of ballast.

3. SCOPE

To measure shear strength, gradation, degree of compaction, particle shape and flakiness the following tests were used:

- **Gradation:** Hudson's Gradation Modulus A was used to index gradations.

- **Particle Shape and Texture** A modified ASTM D 3398 Index Test was used.

- **Compaction:** Three different compactive efforts were used.

- **Flakiness:** The Flakiness Index Test contained in the British Standard 812 was correlated with the Particle Shape Test. Four different flakiness numbers were used.

- **Shear Strength:** A 12 x 12 x 7 inch split direct shear box was used to measure strength. Shear strength tests were done for aggregates with gradation, compaction, particle shape and flakiness.

4. DISCUSSION

4.1 Gradation

The Fuller theoretical ideal grading curve (see Exhibit No. 1) was a gradation designed to produce a maximum density. In this gradation all the gaps have been filled with aggregate. The total gradation included 45% of the sand sized particles. A ballast material graded to the curve would probably produce the highest resistance to shear and mechanical deformation, although the ballast section might be susceptible to moisture retention and frost heave. This was one of the reasons why slag ballasts were sometimes used without screening out the fines. They added to the shear strength, did not absorb water and were not displaced by heavy rains. This was not the case with the fines in crushed rock ballast, especially limestones, as they turn to mud, causing the ballast to become fouled, and they can be displaced by heavy rains.

The ballast gradation presently used in CN Specification 12-20 reflects a continuation of field and economic experience. The basic requirements for ballasts are: to support the track and traffic, to resist being washed away by rain, and to provide drainage, thereby minimizing frost heave. To meet this criteria railway engineers have produced a multitude of gradations.

Ballast Tests Gradation compared to the Fuller Maximum Density Curve

	Gradation Index A	Density Rodded	Density Vibrated
○	1- 1.51	124.4	133.9
△	2- 2.22	137.5	149.0
□	3- 2.58	144.3	161.6
⬡	4- 2.90	153.8	165.6

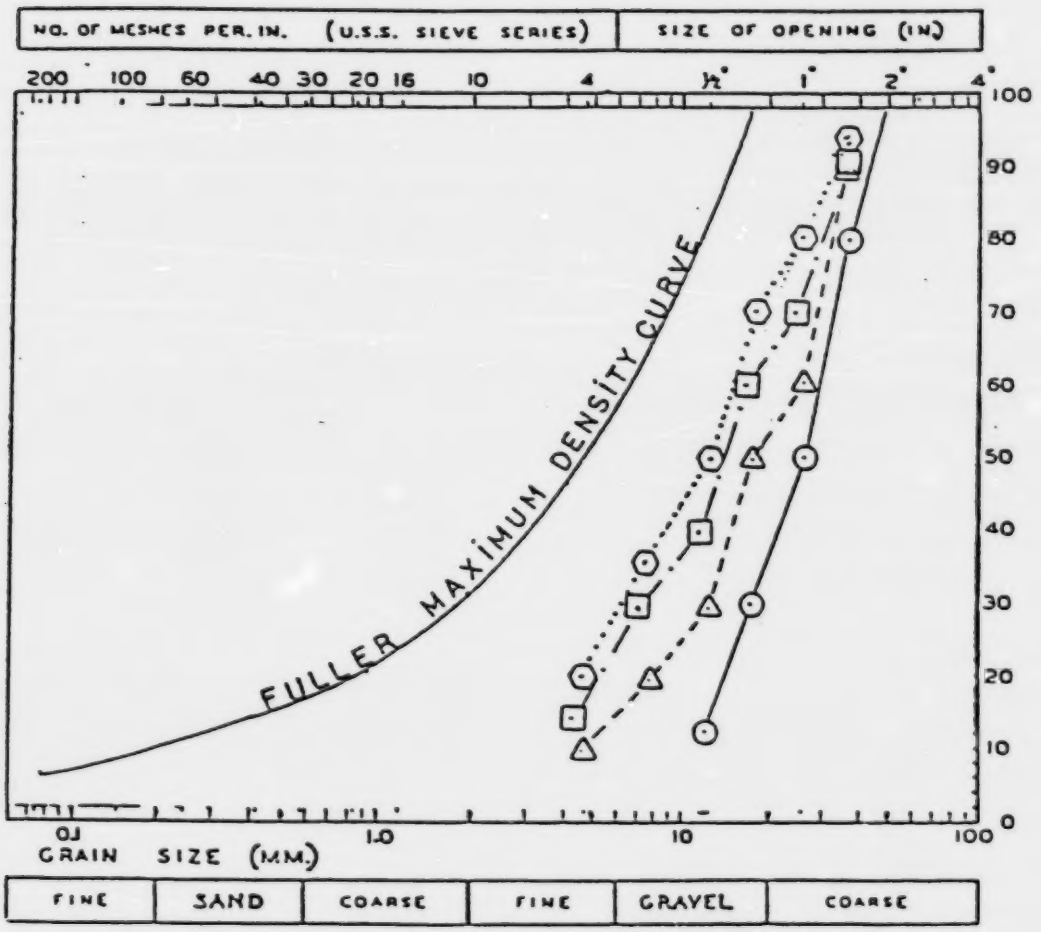
NO. OF MESHES PER. IN. (U.S.S. SIEVE SERIES)
SIZE OF OPENING (IN)
200 100 60 40 30 20 16 10 4 ½" 1" 2" 4"
FULLER MAXIMUM DENSITY CURVE
100 90 80 70 60 50 40 30 20 10 0
0.1 1.0 10 100
GRAIN SIZE (MM.)
FINE SAND COARSE FINE GRAVEL COARSE

EXHIBIT NO. 1

4.1.1 History of Gradation

A look at the many different gradations developed by the railways (see Table No. 1) only added confusion to choosing a proper gradation for a ballast application. To solve this dilemma Canadian National decided in 1969 to use one gradation instead of four.

In 1926 the CN Specification for crushed rock ballast was very coarse. It was composed mainly of large sized particles passing the 3 in. sieve. Ninety percent of the material had to be retained on the 3/4 in. sieve. These limits proved to be expensive, as a lot of material passing the 3/4 in. sieve was wasted. In 1944 CN changed the specifications to include 4 different gradings (see Table No. 1). The question would arise when to use ballast No. 24 and when to use ballast No. 6, or No. 5, or No. 4. One might conclude that the actual gradation was not so important for crushed rock ballast. In 1969 CN changed its specifications to provide a single grading, designated as Grading A. This specification included some small aggregate and the gradation requirements were in between the old No. 5 and No. 6, 1944 specifications. Experience by CN geotechnical engineers in the field found this gradation to be too fine and it was changed to a coarser grading similar to the old No. 4 ballast. This is the grading in use today. Table No. 3 shows some of the gradings used by CN and AREA specifications.

4.1.2 Hudson's Gradation Modulus A

In most specifications, aggregate gradations are specified by a range of percentages for different sieve sizes. To compare one gradation to another, it would be necessary to plot a curve for each gradation and compare each individual size. How much simpler it would be if a gradation could be described between a range of two numbers.

TABLE NO. 1

RAILWAY BALLAST SPECIFICATIONS

Specification	Year	Ballast No.	Size Range
CN ballast	1926	--	3" - 1/2"
"	1944	24	3" - 3/8"
"	1944	4	2" - 3/8"
"	1944	5	1-1/2" - #4
"	1944	6	1" - #4
"	1969	A	1-1/2" - #4
"	1981	A	2" - #4
AREA	1978	24	3" - 3/8"
"	1978	3	2-1/2" - 3/8"
"	1978	4	2" - #4
"	1978	5	1-1/2" - #8
"	1978	57	1-1/2" - #16

Exhibit No. 1 is a graph showing the Fuller Maximum Density Curve and the gradings that were tested in the direct shear box.

In these ballast studies where strength was being measured for specific gradations, a factor was needed that would characterize a gradation by a single number, rather than a multiplicity of percentages. In addition, it was required that the factor would apply to the entire range of ballast gradations and would be easy to compute. It should be applicable to any graded aggregate, regardless of the sieves used to define the gradation. The gradation modulus A used by Hudson meets this criteria and has a wide application. This index number accurately describes the CN ballast specificaton limits.

4.1.3 Methodology

The gradation modulus A is defined as the logarithm to the base 2, of the ratio of an arbitrary constant to the effective mean diameter in millimeters of a collection of aggregate particles. The constant 54.8 is the effective mean diameter of the largest size group (3 in. - 1-1/2 in.) in the series of size groups under consideration and is represented as

$$B = \frac{0.4343\ (d1 - d2)}{\log\ (d1/d2)}$$

where d1 = opening size of largest sieve

d2 = opening size of 2nd largest sieve

The symbol A was selected because the modulus is the grand average of the effective mean diameter of a series of groups of particles.

The gradation modulus A is expressed as

$$A = \frac{\log B - \log d}{\log 2}$$

In the case of the railway ballast, the largest size sieve to be used in the foreseeable future is 3 in. In this case the value for B is 54.8 and the gradation modulus,

$$A = \frac{\log 54.8 - \log d}{\log 2}$$

where

$$d = \frac{0.4343\ (d1 - d2)}{\log d1/d2}$$

In which

d = mean diameter of aggregate particle in each gradation

d1 = size of openings in largest sieve

d2 = size of openings in the next sieve size smaller than d1

The value B of 54.8 is constant for all calculations of the gradation modulus A. The value of d and A must be calculated for each size fraction. The individual values of A are summed for each sample and the total reported as the gradation modulus for the grading under study.

For each size fraction a value for A is calculated. The individual values of A are summed and the total reported as the gradation modulus A for the gradation under study. A sample of the calculations and a Simplified Method for using Hudson's Gradation Modulus A with CN Ballast Specification is given in Table No. 2.

4.1.4 A Simplified Method for Using Hudson's Gradation Modulus A with CN Ballast Specification 12-20

A standard sieve analysis must be done using the sieves specified in CN Ballast Specification 12-20. The A factor has been calculated for each sieve as shown in Table 2. The A factor must be used with the sieve to which it is assigned. Expressed as a decimal, the percent retained is multiplied by the A factor producing a weighted A number. This is repeated until all the sieving has been done and 100% of the sample has been weighted. The sum of the weighted numbers is the Gradation Modulus A. Table No. 3 demonstrates the calculations.

TABLE NO. 2

HUDSON'S MOLDULUS A CALCULATIONS WITH CN BALLAST SPECIFICATION 12-20

Sieve Size	Percent Passing		Percent Retained	A Factor	A Weighted
	CN Specifications	Ballast Sample	Ballast Sample		
2"	100		0	0.29	0
1-1/2"	80 - 100	90	10	0.67	.067
1"	30 - 75	50	40	1.16	.464
3/4"	15 - 40	30	20	1.67	.334
1/2"	0 - 20	10	20	2.17	.434
3/8"	0		10	2.67	.267
#200	0 - 1				A = 1.57
	A 1.29 to A 1.87				

Using this technique the CN Specifications can be reduced to two numbers, A 1.29 and 1.87, and the specific Ballast Sample can be reduced to one number, A 1.57. To meet CN Specifications the ballast A number must be at least 1.29 and not greater than 1.87.

The usefulness of this method becomes clear when comparing different gradations as shown in Table No. 3.

When comparing the CN Specification for ballast to other ballast gradations the task was made simpler by using Hudson's Index Numbers. It has been shown in Table 3 that the CN 1981 Specification (still in force) falls approximately midpoint in coarseness when compared to other gradations. It was decided to do an investigation to see how different gradations affect the shear strength of ballast.

4.2 Particle Shape and Texture

Generally, the geometric characteristics embracing shape, angularity, and surface texture of ballast aggregates were described with such words as rounded, flat, irregular, angular, smooth, glassy or rough. A test method was needed to describe the geometric characteristics embracing shape, angularity, and surface texture of coarse aggregates. These had to be quantitatively evaluated.

This method covers the determination of the particle index of an aggregate as an overall measure of particle shape and texture characteristics. It was decided to use 1/2 in. aggregate from four different sources: (1) an uncrushed rounded slag with a smooth surface texture, (2) a flat crushed trap rock with a rough surface texture, (3) a blocky crushed limestone with a rough surface texture, and (4) a rounded uncrushed selected gravel with a smooth surface texture. The samples are listed in Table No. 4.

TABLE NO. 3

SUMMARY OF HUDSON'S GRADATION A WITH DIFFERENT SPECIFICATIONS

Spec.	Year	No.	Size Range	Gradation Index A	
				Range	Average
CN	1926	--	2-3/4" - 1/2"	--	Max. A 0.87
"	1944-63	24	3" - 3/8"	A 0.66 - A 1.12	A 0.89
"	1944-63	4	2" - #4	A 1.21 - A 1.62	A 1.42
"	1944-63	5	1-1/2" - #4	A 1.90 - A 2.55	A 2.22
"	1944-63	6	1" - #4	A 2.25 - A 2.68	A 2.47
"	1969	A	1-1/2" - #4	A 1.98 - A 2.66	A 2.32
"	1981*	A	2" - #4	A 1.29 - 1.87	A 1.58
AREA	1978	24	3" - 3/8"	A 0.66 - A 1.12	A 0.89
"	1978	3	2-1/2" - 3/8"	A 0.82 - A 1.16	A 0.99
"	1978	4	2" - #4	A 1.21 - A 1.62	A 1.42
"	1978	5	1-1/2" - #8	A 1.78 - A 2.37	A 2.08
"	1978	57	1-1/2" - #16	A 2.19 - A 2.82	A 2.51
Noranda Slag			2-1/2" - #200	--	A 2.88
International Nickel Slag			2-1/2" - #200	--	A 2.92
Fuller			1-3/4" - #200	--	A 3.11

*Note: The 1981 CN specifications are still in effect with an average index number of A 1.58. If you add the 1% passing the #200 it will be 1.62.

TABLE NO. 4

SHAPE AND TEXTURE OF AGGREGATES

No.	Aggregate	Shape	Texture
1	Slag	Rounded	Smooth
2	Trap Rock	Flat	Rough
3	Limestone	Blocky	Rough
4	Gravel	Round	Smooth

4.2.1 Equipment

An aluminum sample container was made with a diameter of 6.09 in. and a height of 8.0 in. A reference line was inscribed 7.0 in. above the bottom to mark the approximate top of the sample. To measure the initial sample volume, and to overcome the difficulties in measuring an irregular surface presented by ballast, a system was developed using a water filled balloon under air pressure. The balloon was fitted to the bottom of the sample container lid; water was supplied through the lid to the balloon from a graduated plastic reservoir.

A pressure of 3 psi was controlled by regulated air pressure on the top of the water reservoir and read out on a mercury manometer. Vacuum was used to evacuate water from the balloon during the setting up and dismantalling operations. A schematic of the balloon volume measurement device is shown in Exhibit No. 2.

The tamping rod was a round straight steel rod having a diameter of 0.625 $\pm$ 0.010 in., weighing 930 $\pm$ 10 grams, and approximately 24 in. long. One hundred percent of the material passed the 3/4 in. sieve and was retained on the 1/2 in. sieve. The bulk dry specific gravity of the sample was determined in accordance with the ASTM Method C127.

4.2.2 Procedure

The samples were compacted to two densities as follows. The aggregate was placed in the mold in 3 layers: each layer was tamped 10 times with the tamping rod. The rod was held 2 inches vertically above the sample and dropped. After the final layer had been compacted, the mold and sample were weighed and the net weight of the sample was determined. This procedure was repeated using the same sample and the average weight of the two tests was calculated.

To obtain a higher density the same procedure was followed except the sample was tamped 50 times instead of 10. Again the average weight of two tests was determined.

The voids in the aggregate were calculatd at 10 drops per layer and at 50 drops per layer, respectively, by the following relationships:

$V_{10} = [1-(W_{10}/SV)] \times 100$

$V_{50} = [1-(W_{50}/SV)] \times 100$

V_{10} = voids in aggregate compacted at 10 drops per layer %

V_{50} = voids in aggregate compacted at 50 drops per layer %

W_{10} = average net weight of the aggregate in the mold compacted at 10 drops perlayer g

W_{50} = average net weight of the aggregate in the mold compacted at 50 drops per layer g

S = bulk dry specific gravity of the aggregate

V = volume of the cylindrical mold ml.

The particle index Ia was calculated using the following formula:

$$Ia = 1.25\ V_{10} - 0.25\ V_{50} - 32.0$$

PARTICLE SHAPE INDEX TEST

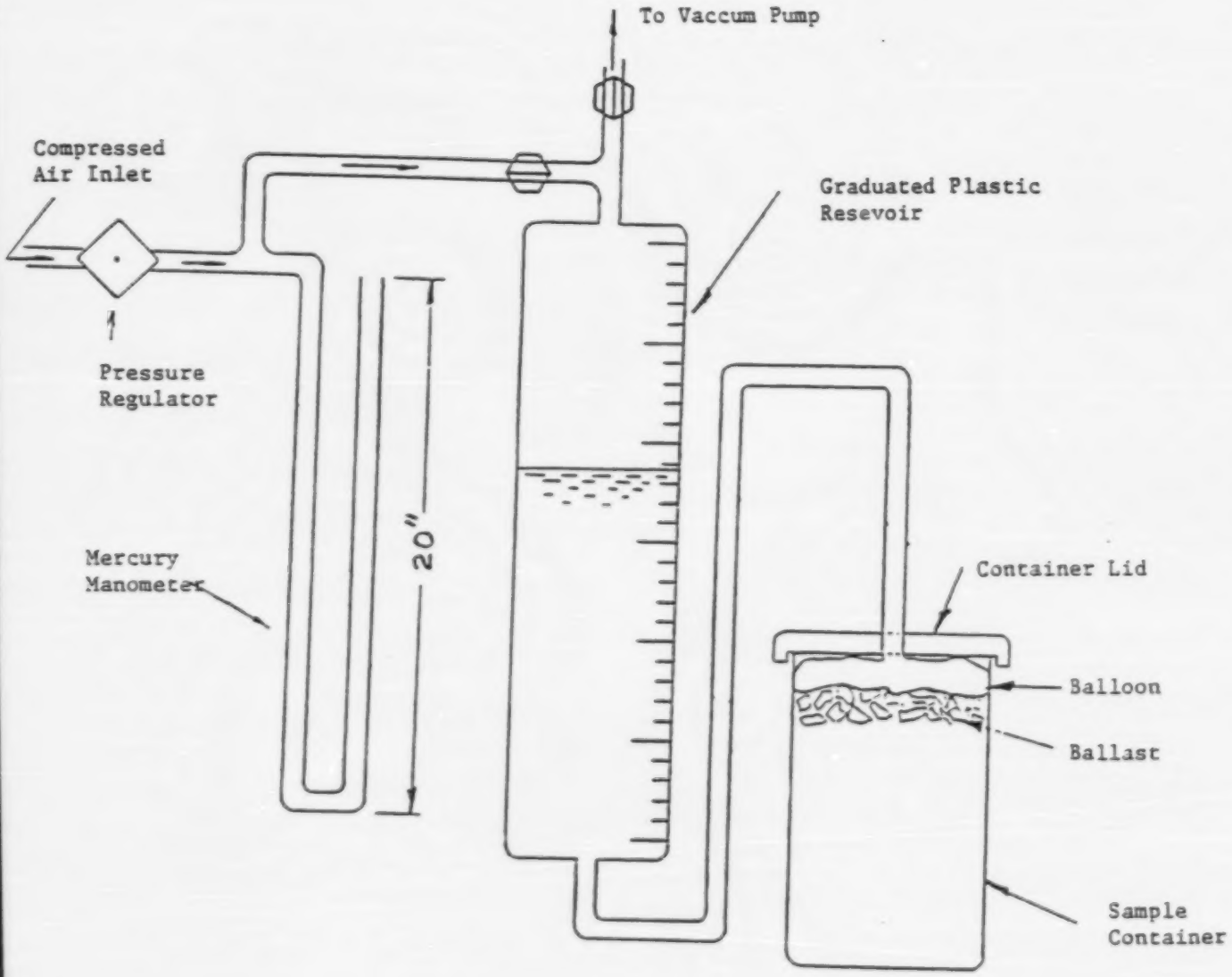

DIAGRAM OF SAMPLE VOLUME
MEASURING SYSTEM

EXHIBIT NO. 2

4.3 Flakiness Index

The Flakiness Index of an aggregate is the percentage by weight of particles whose least thickness is less than 3/5 of their mean thickness. The present CN ballast specification requires that a crushed rock ballast shall contain less than 30% by mass of flat pieces. The test method "Determination of Flakiness Index" is contained in British Standard 812. Flat and elongated pieces break easier than round or blocky particles. This test has been useful in keeping these particles to an acceptable level. It was felt that it might be useful to compare this test to the Particle Shape Index test to see if a correlation could be made. Exhibit No. 3 shows the Flakiness Thickness Gauge used in the Flakiness Index test.

4.4 Shear Strength

The most important physical property of a ballast material is in its resistance to shear deformation. Shear strength is defined as the resistance to deformation by continuous shear displacements of material particles or masses by the action of a tangential stress. The strength of a ballast material comes from solid friction, sliding, rolling or interlocking between particles. Ability of a ballast to slide, roll or to interlock is affected by factors other than those provided in standard tests. This investigation showed the relationship to shear strength between the following factors: gradation, shape, surface roughness, and compaction.

FLAKINESS THICKNESS GAUGE

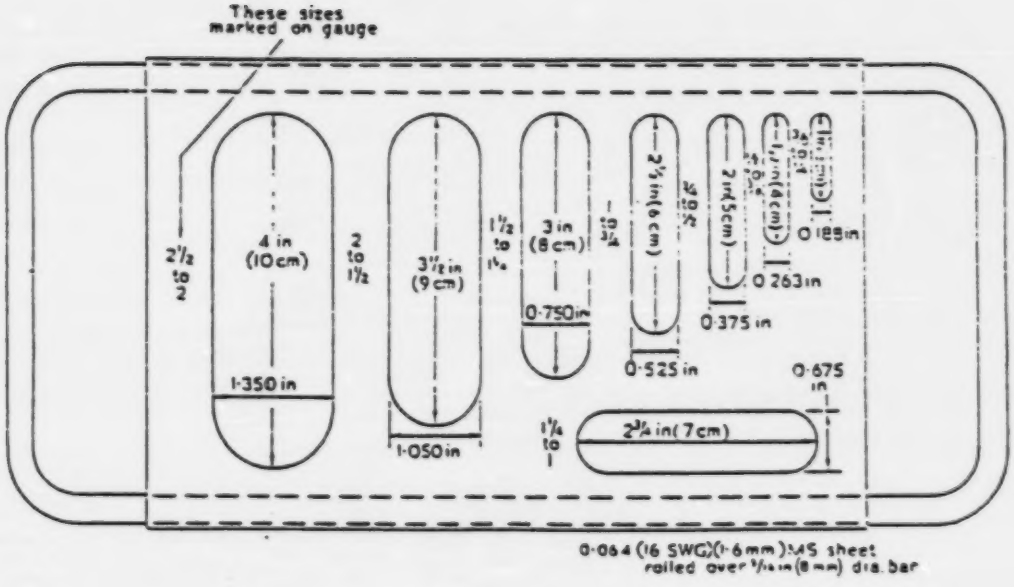

EXHIBIT NO. 3

4.4.1 Equipment

A large direct shear box was used to measure ballast shear strength. It was comprised of a shear container 12 inches by 12 inches square by 7-1/4 inches high mounted on a friction reducing bearing. The box was split in two, each half was 3-5/8 inches in height. The bottom half was driven by a variable speed transmission to provide a constant rate of displacement along the shear plane. To provide a normal load, a double acting hydraulic cylinder was activated by a pump rated at 10,000 psi. Two strain gauged steel arms were used to hold back the top portion of the shear box and act as load cells. A balanced Wheatsone bridge with four strain gauges was essentially the circuitry of the load cell. When calibrated properly, the bridge responded to pressure changes by a proportional change in resistance that imbalanced the bridge and varied the output voltage. This was calibrated as the shear stress and was recorded on a strip recorder.

4.4.2 Procedure

A ballast sample was placed into the shear container filling one-third of the box. The sample was either loose, vibrated for one minute, or compacted with a steel rod 50 times. Another one-third was added, either loose, vibrated or rodded and then the final lift was added, filling the box. Filling of the box was continued during the final compaction operation so that the box, after completing the one minute vibration or the 50 blows, remained full. A gap of 0.20 inch was created along the shear plane. The top plate and yoke was placed on top of the sample and a normal vertical load was applied. At this stage the sample was ready to test. The strain rate was constant at 0.3 inch per minute for all tests.

5. TESTING PROGRAM

5.1 Shear Strength

A large direct shear box was used to measure the shear strength of ballast. Different gradations, particle shapes, densities and normal loads were used to evaluate their effect on shear strength.

5.2 Gradation

To test the effect gradation has on the strength of ballast, it was decided to test four different gradations. Hudson's Gradation Index No. was made use of to classify them as follows: 1.51, 2.22, 2.58, and 2.90. A slag ballast was selected because of its toughness, and it would breakdown less under harsh shear testing conditions. Two normal loads and two compactive efforts were each tested five times. Table No. 5 lists the Gradation Index No. A, the Normal Load, the Compaction and the number of tests.

TABLE NO. 5

SHEAR vs GRADATION

Material	Gradation Index A	Normal Load (psi)	Compaction	No. of Tests
Slag	1.51	6.94	Rodded	5
"	2.22	6.94	"	5
"	2.58	6.94	"	5
"	2.90	6.94	"	5
"	1.51	6.94	Vibrated	5
"	2.22	6.94	"	5
"	2.58	6.94	"	5
"	2.90	6.94	"	5
"	1.51	20.8	Rodded	5
"	2.22	20.8	"	5
"	2.58	20.8	"	5
"	2.90	20.8	"	5
"	1.51	20.8	Vibrated	5
"	2.22	20.8	"	5
"	2.58	20.8	"	5
"	2.90	20.8	"	5

5.3 Particle Shape and Texture

Four different particle shapes, two normal loads, two densities for four separate materials were tested to evaluate the effect particle shape has on shear strength. Table No. 6 lists the number of tests, materials and test conditions.

TABLE NO. 6

SHEAR vs PARTICLE SHAPE

Material	Particle Shape No.	Normal Load (psi)	Compaction	No. of Tests
Slag	7.23	6.94	Rodded	5
"	7.23	6.94	Vibrated	5
"	7.23	20.8	Rodded	5
"	7.23	20.8	Vibrated	5
Trap Rock	16.83	6.94	Rodded	5
"	16.83	6.94	Vibrated	5
"	16.83	20.8	Rodded	5
"	16.83	20.8	Vibrated	5
Limestone	13.7	6.94	Roded	5
"	13.7	6.94	Vibrated	5
"	13.7	20.8	Rodded	5
"	13.7	20.8	Vibrated	5
Gravel	5.75	6.94	Rodded	5
"	5.75	6.94	Vibrated	5
"	5.75	20.8	Rodded	5
"	5.75	20.8	Vibrated	5

5.4 Compaction

To evaluate the effect compaction had on a particular aggregate, a crushed limestone aggregate was selected. Three levels of compaction, three normal loads, and two gradations were tested in the direct shear box as listed in Table No. 7.

TABLE NO. 7

SHEAR vs COMPACTION

Material	Gradation Index A	Normal Load (psi)	Compaction	No. of Tests
Crushed Limestone	2.32	6.94	Loose	5
"	1.43	6.94	"	5
"	2.32	6.94	Rodded	5
"	1.43	6.94	"	5
"	2.32	6.94	Vibrated	5
"	1.43	6.94	"	5
"	2.32	13.9	Loose	5
"	1.43	13.9	"	5
"	2.32	13.9	Rodded	5
"	1.43	13.9	"	5
"	2.32	13.9	Vibrated	5
"	1.43	13.9	"	5
"	2.32	20.8	Loose	5
"	1.43	20.8	"	5
"	2.32	20.8	Rodded	5
"	1.43	20.8	"	5
"	2.32	20.8	Vibrated	5
"	1.43	20.8	"	5

6. TEST RESULTS

In Exhibits Nos. 4 and 5 the broader ranged sample with a Gradation Modulus of A 2.90 produced the highest shear strength and the highest density. Conversely, the largest gap-graded ballast with a Gradation Modulus of A 1.51 generally produced lower shear strengths. Table No. 8 shows that the broader ranged ballast gradation increased shear strength from 0% to 60% over the gap-graded ballast. In this Table, the largest gap-grading taken as 100% was compared to the finest broad-grading.

TABLE NO. 8

PERCENT INCREASE IN SHEAR STRENGTH
(BROADEST) FINEST GRADATION/COARSEST GRADATION (GAP-GRADED)

Percent Strain	Rodded Compaction					
	Normal Load					
	6.94 psi			20.83 psi		
	Gradation Index		Percent Increase	Gradation Index		Percent Increase
	1.51	2.94		1.51	2.94	
1	8.0	8.0	0	11.8	16.8	42
2	10.3	10.3	0	16.3	23.1	42
Vibrated Compaction						
1	9.0	14.4	60	23.2	27.4	18
2	11.7	15.5	33	29.2	31.6	8

DIRECT SHEAR TESTS ON BALLASTS

STRESS VS. STRAIN CURVE

RODDED COMPACTION

SLAG BALLAST

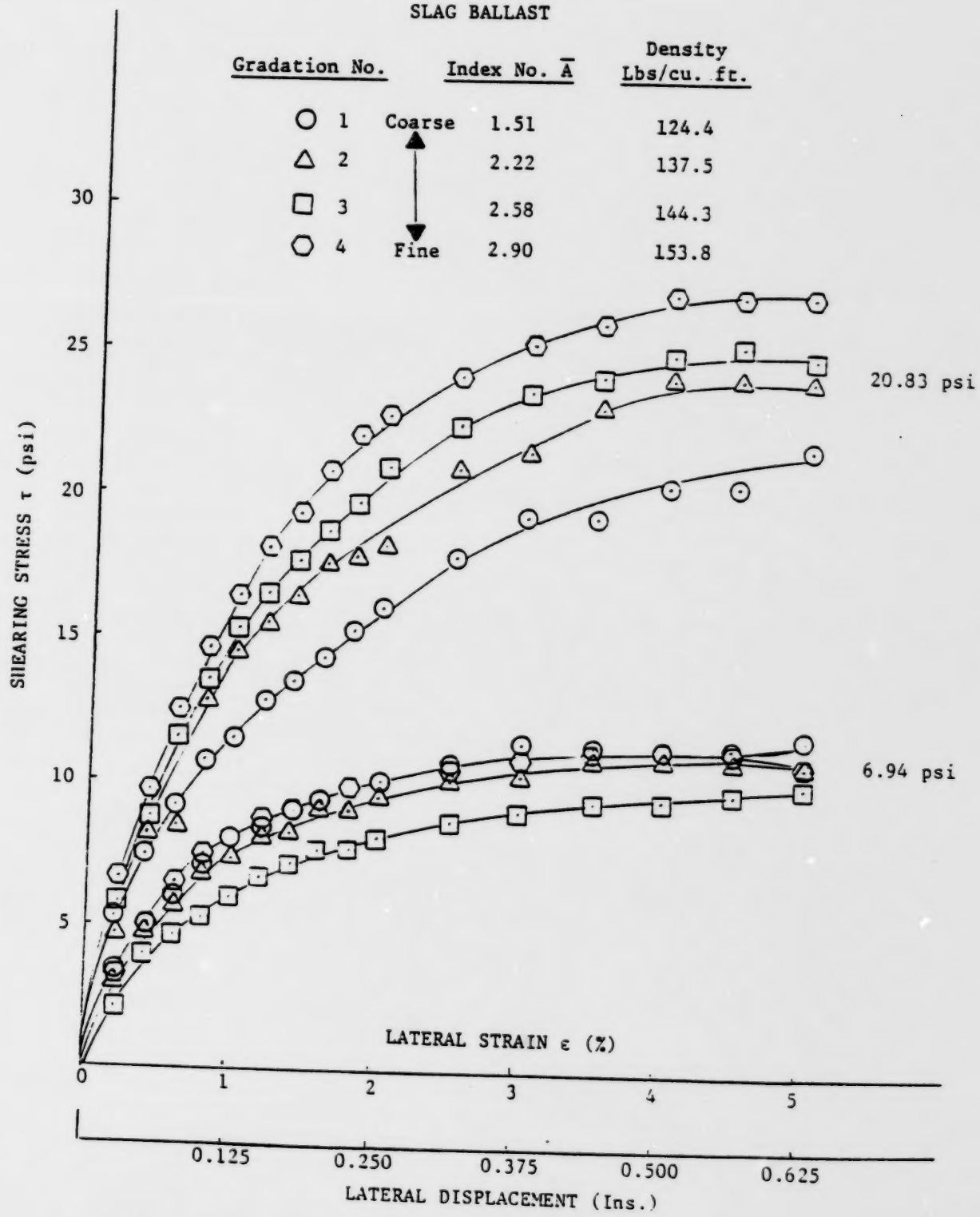

EXHIBIT NO. 4

DIRECT SHEAR TESTS ON BALLASTS

STRESS VS. STRAIN CURVES

VIBRATED COMPACTION

SLAG BALLAST

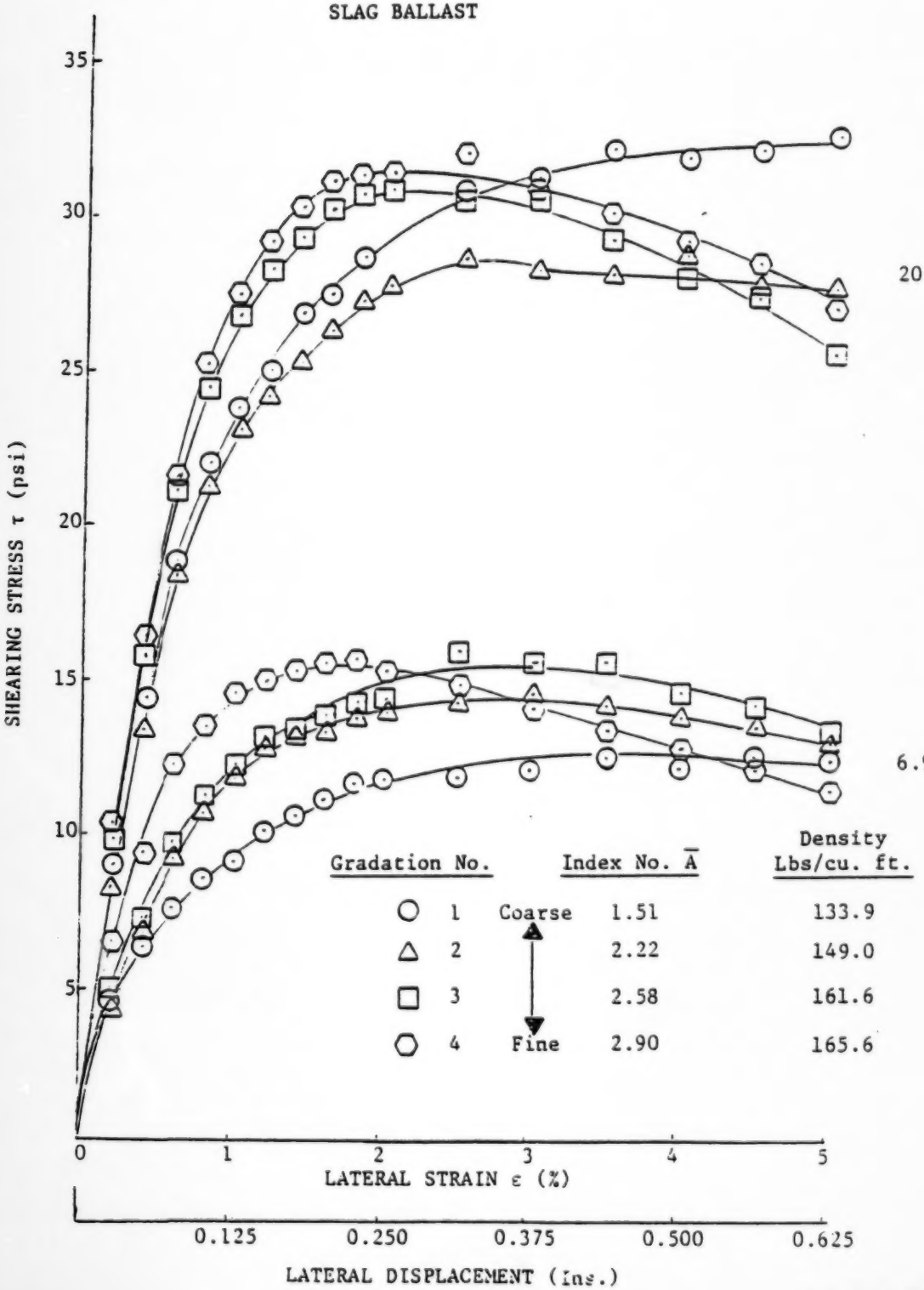

EXHIBIT NO. 5

Broader ranged ballasts achieved a higher density than gap-graded coarser ballasts. This can be seen in Table No. 9 and Exhibits No. 4 and 5, where an increase of 1.0 A in the Gradation Index increased the density by approximately 22 lbs. per cubic foot.

TABLE NO. 9

GRADATION INDEX A vs DENSITY

Gradation Index A	Density, lb./cu. ft.	
	Rodded	Vibrated
1 - 1.51	124.4	133.9
2 - 2.22	137.5	149.0
3 - 2.58	144.3	161.6
4 - 2.90	153.8	165.6

The benefits of increased compaction were substantial. An average of 53% increase in shear strength was experienced from a loose state to a rodded compacted state. An average increase of 77% was experienced from a rodded state to a vibrated compacted state. Exhibit No. 9, Density vs Hudson's Gradation A, shows the effect that an increase in Hudson's A index increases the density and an increased compactive effort increases the density. Table No. 10 is an analysis of Exhibits No. 6, 7, and 8.

DIRECT SHEAR TESTS ON BALLAST

STRESS VS STRAIN CURVES

LOOSE COMPACTION

LIMESTONE AGGREGATE

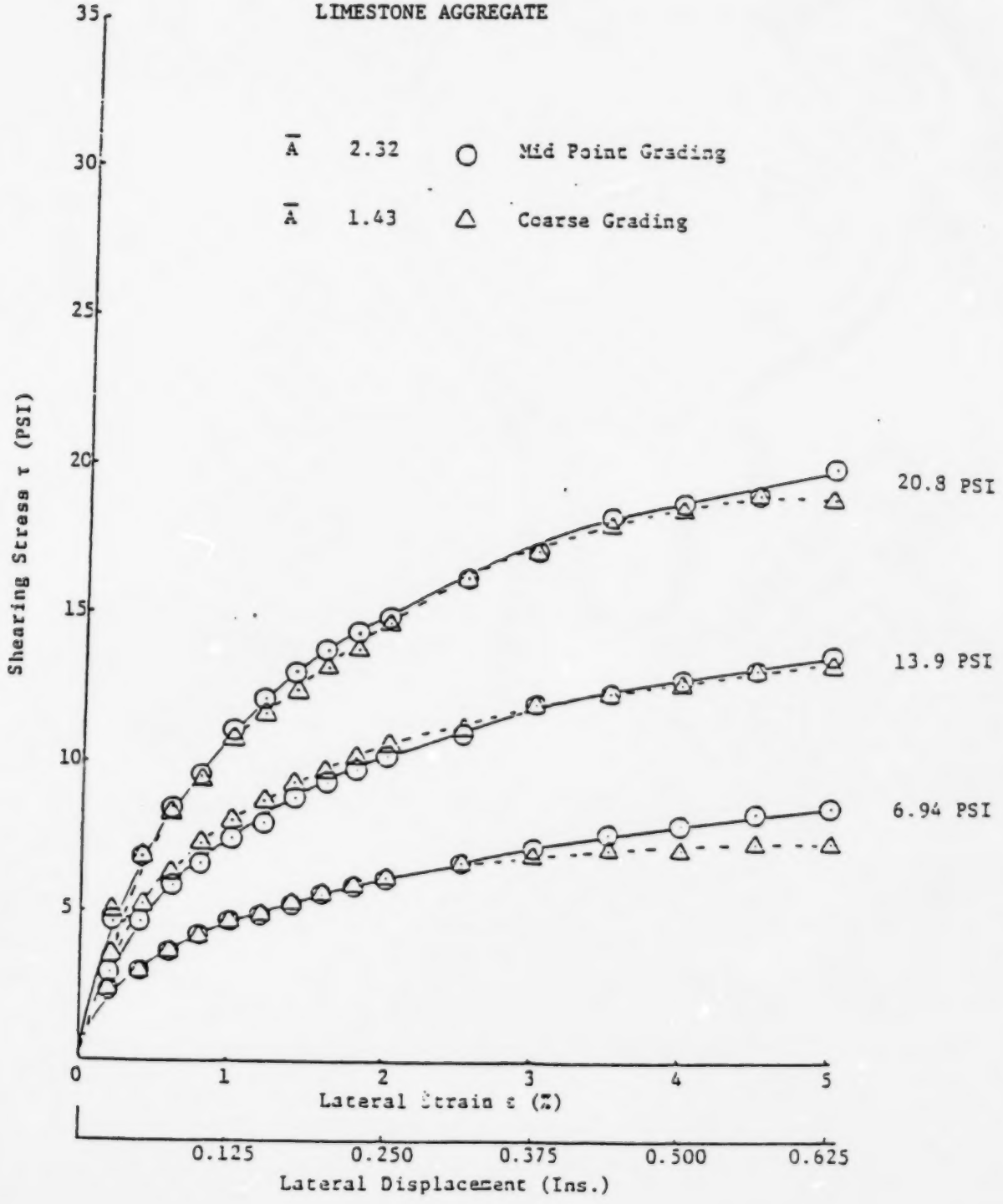

EXHIBIT NO. 6

DIRECT SHEAR TESTS ON BALLAST

STRESS VS. STRAIN CURVES

RODDED COMPACTION

LIMESTONE AGGREGATE

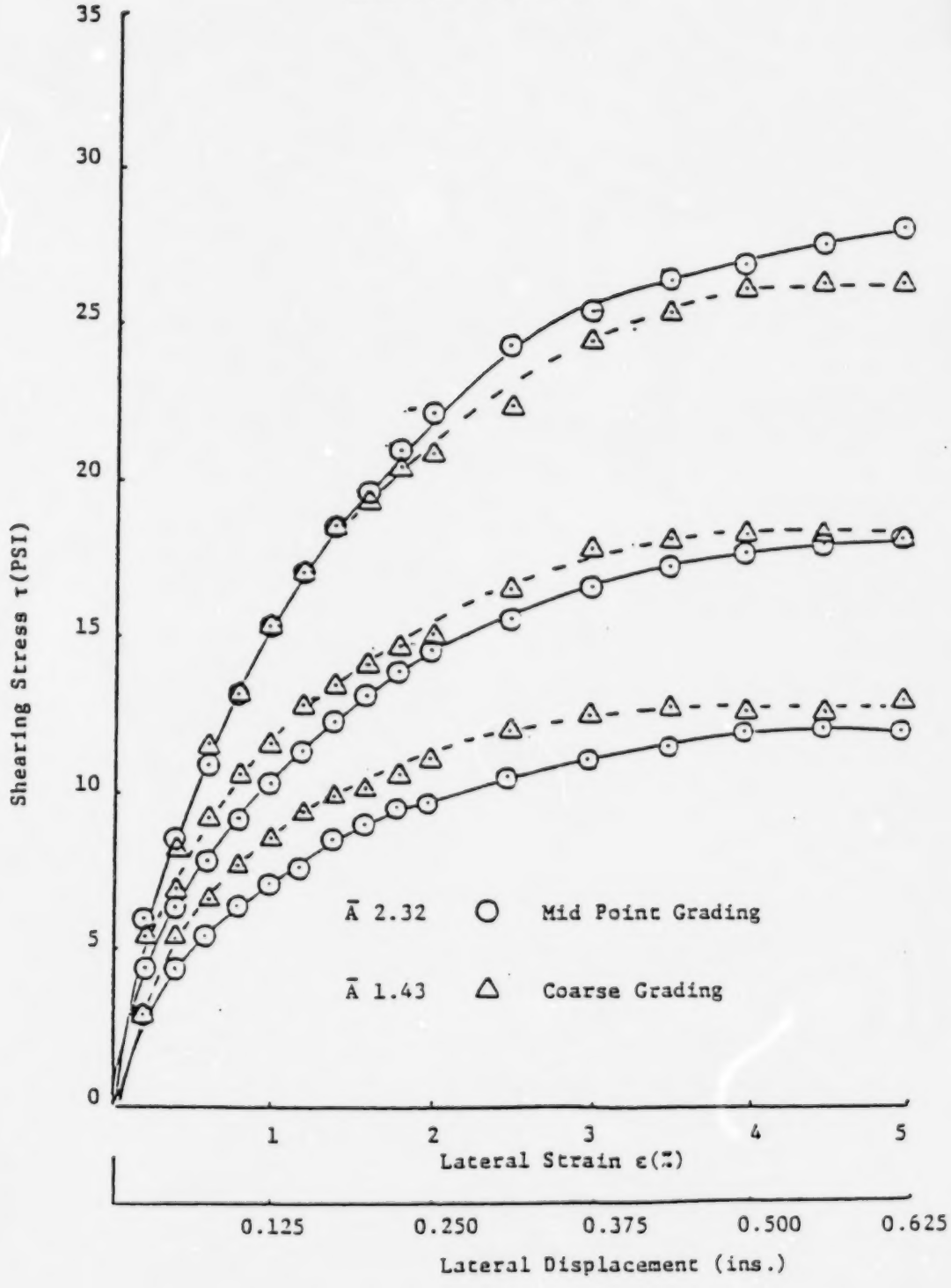

EXHIBIT NO. 7

DIRECT SHEAR TESTS ON BALLAST
STRESS VS. STRAIN CURVES
VIBRATED COMPACTION
LIMESTONE AGGREGATE

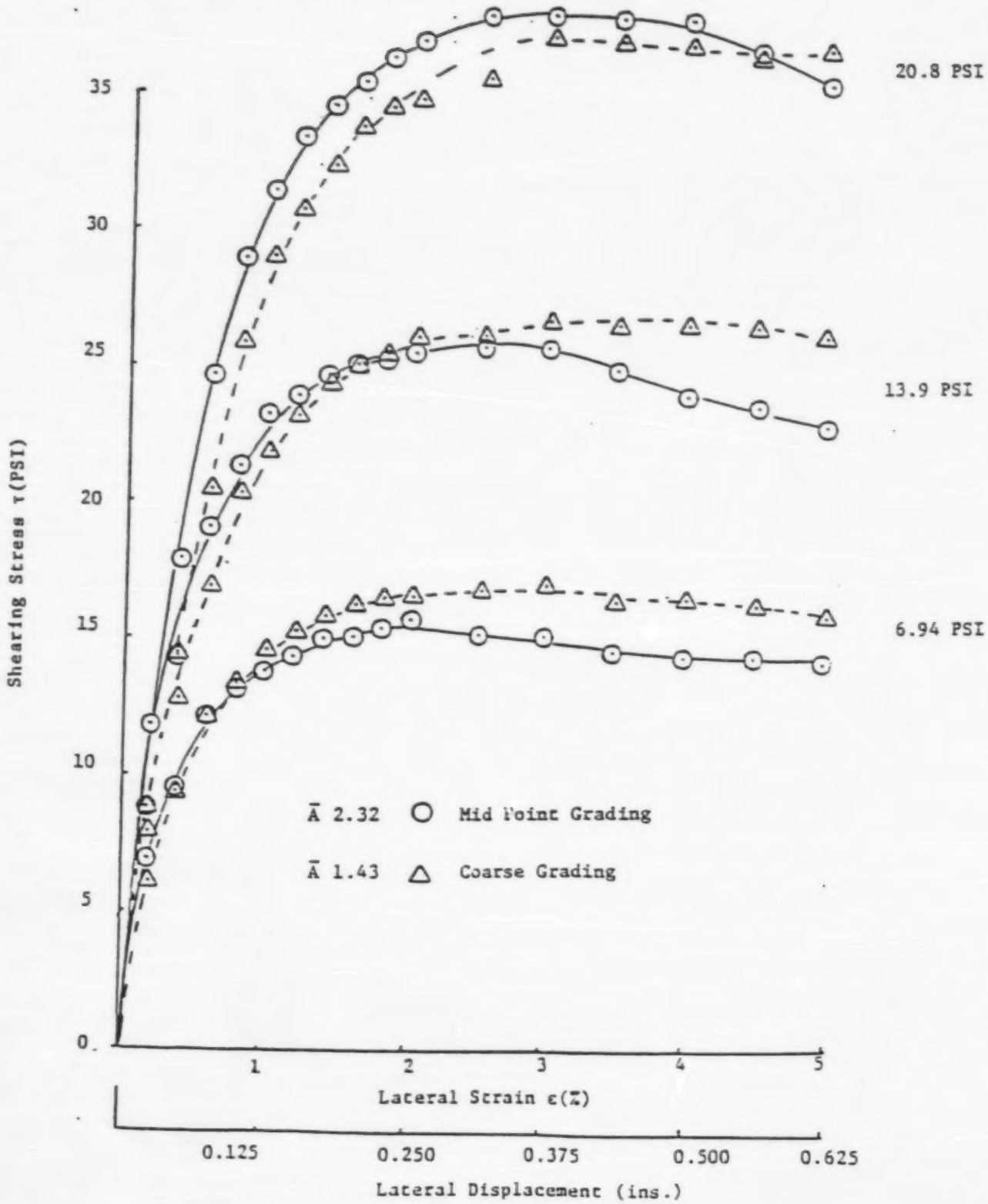

EXHIBIT NO. 8

DENSITY/HUDSON'S GRADATION $\bar{A}$

SLAG BALLAST

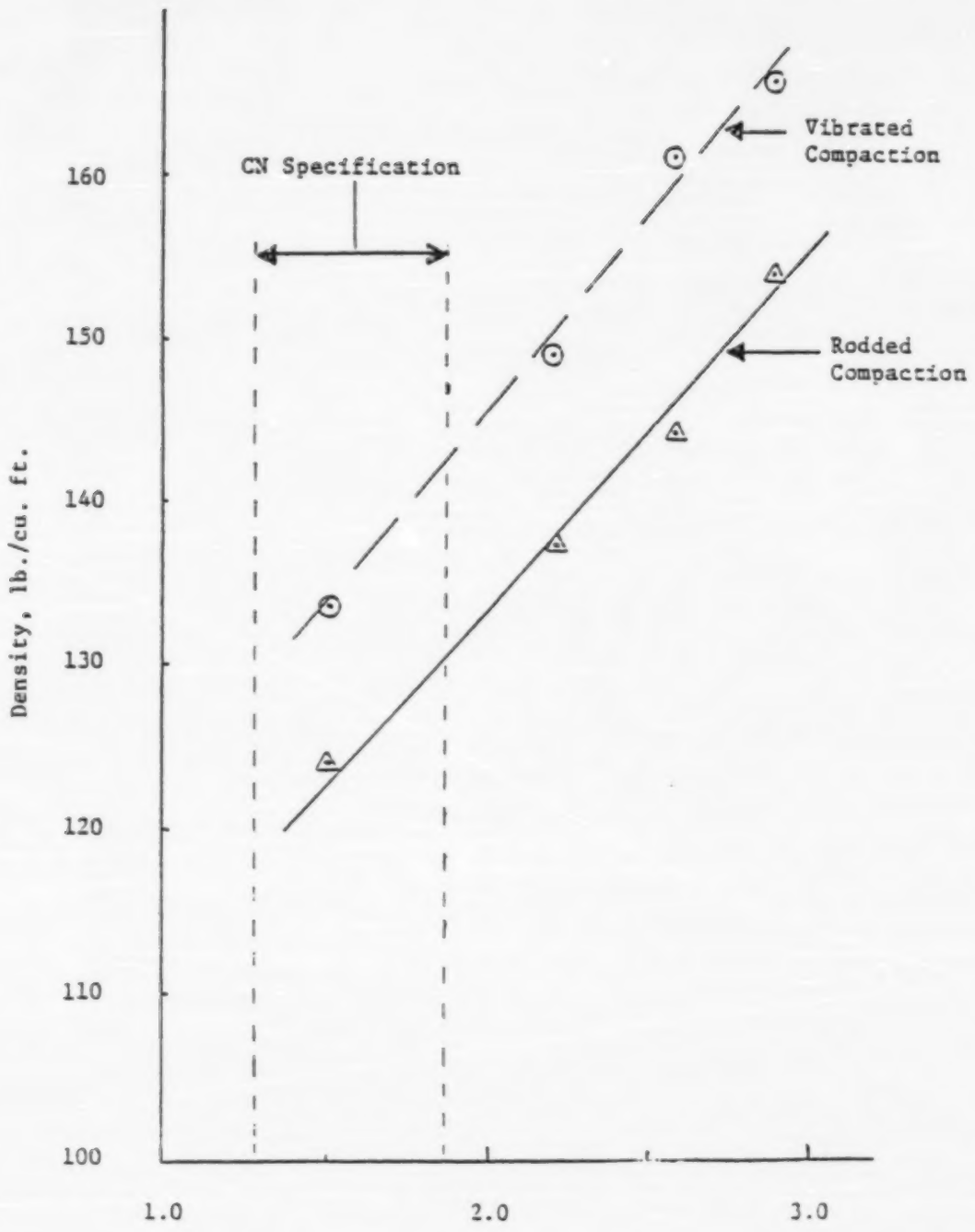

EXHIBIT NO. 9

TABLE NO. 10

EFFECT OF COMPACTION ON SHEAR STRENGTH (LIMESTONE)

Normal Load	Rodded/Loose 1% Strain			Vibrated/Rodded 1% Strain		
	Average of Gradings		Percent Increase	Average of Gradings		Percent Increase
	Loose psi	Padded psi		Padded	Vibrated	
6.94	4.6	7.8	69	7.8	14.3	83
13.9	7.6	11.0	45	11.8	22.3	89
20.8	11.0	15.3	38	15.3	29.8	95
	2% Strain			2% Strain		
6.94	6.0	10.4	73	10.4	16.0	54
13.9	10.3	15.0	46	15.0	25.7	71
20.8	14.6	21.3	46	21.3	36.0	69
Average			53			77

Aggregates with distinct physical features responded differently to various levels of compaction. The gravel aggregate with features that can be easily compacted (round, smooth) produced a higher resistance to shear than the samples with features that prevented them from responding well to a light compacted effort (Exhibit No. 10, slag - heavy, trap rock - flat, and limestone - rough). In Table No. 11 (an analysis of Exhibit No. 10) the rounded gravel shear strength was compared to the combined average shear strength of slag, trap rock and limestone.

TABLE NO. 11

GRAVEL SHEAR STRENGTH COMPARED TO THE AVERAGE OF SLAG, TRAP ROCK AND LIMESTONE SHEAR STRENGTH

Light Rodded Compaction		
Percent Strain	Normal Load	
	6.94 psi	20.83 psi
1%	29% Increase in Shear Strength	25% Increase in Shear Strength
2%	18% Increase in Shear Strength	11% Increase in Shear Strength

In the light rodded compaction mode at 1% and 2% strain, the rounded gravel had the highest shear strength of the four samples.

Aggregates with good interlocking features responded well with heavy vibrated compactive efforts. The limestone aggregate with rough blocky features had the highest shear strength in the heavy vibrated compacted mode. In Table No. 12 (an analysis of Exhibit No. 11), the limestone aggregate was compared to the combined average shear strength of the aggregates whose features did not respond as well (slag - smooth, trap rock - flat, gravel - round and smooth) under a heavy vibrated compactive effort.

TABLE NO. 12

LIMESTONE SHEAR STRENGTH COMPARED TO THE AVERAGE OF SLAG, TRAP ROCK, AND GRAVEL SHEAR STRENGTH

Vibrated Compaction		
Percent Strain	Normal Load	
	6.94 psi	20.83 psi
1%	9% Increase in Shear Strength	20% Increase in Shear Strength
2%	20% Increase in Shear Strength	13% Increase in Shear Strength

DIRECT SHEAR TESTS ON BALLASTS
STRESS VS. STRAIN CURVES
RODDED COMPACTION

	AGGREGATE	PARTICLE SHAPE INDEX NO.	SHAPE	TEXTURE	DENSITY LBS./CU. FT
○	SLAG	7.23	ROUNDED	SMOOTH	116.9
△	TRAP ROCK	16.83	FLAT	ROUGH	95.2
□	LIMESTONE	13.7	BLOCKY	ROUGH	105.1
⬡	GRAVEL	5.75	ROUND	SMOOTH	103.9

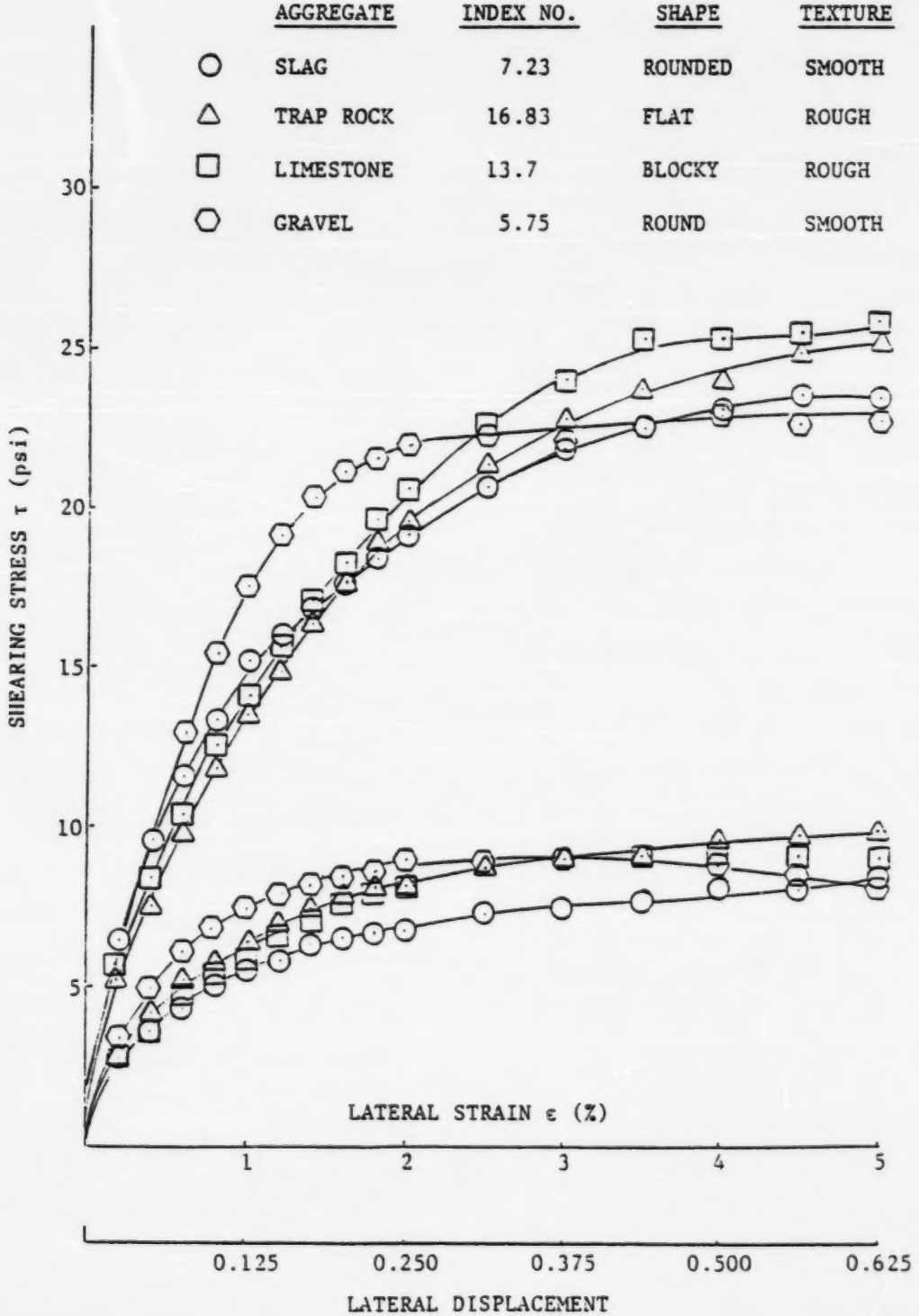

EXHIBIT NO. 10

DIRECT SHEAR TESTS ON BALLASTS
STRESS VS. STRAIN CURVES
VIBRATED COMPACTION

	AGGREGATE	PARTICLE SHAPE INDEX NO.	SHAPE	TEXTURE	DENSITY LBS/CU. FT.
○	SLAG	7.23	ROUNDED	SMOOTH	131.0
△	TRAP ROCK	16.83	FLAT	ROUGH	106.3
□	LIMESTONE	13.7	BLOCKY	ROUGH	107.3
⬡	GRAVEL	5.75	ROUND	SMOOTH	111.6

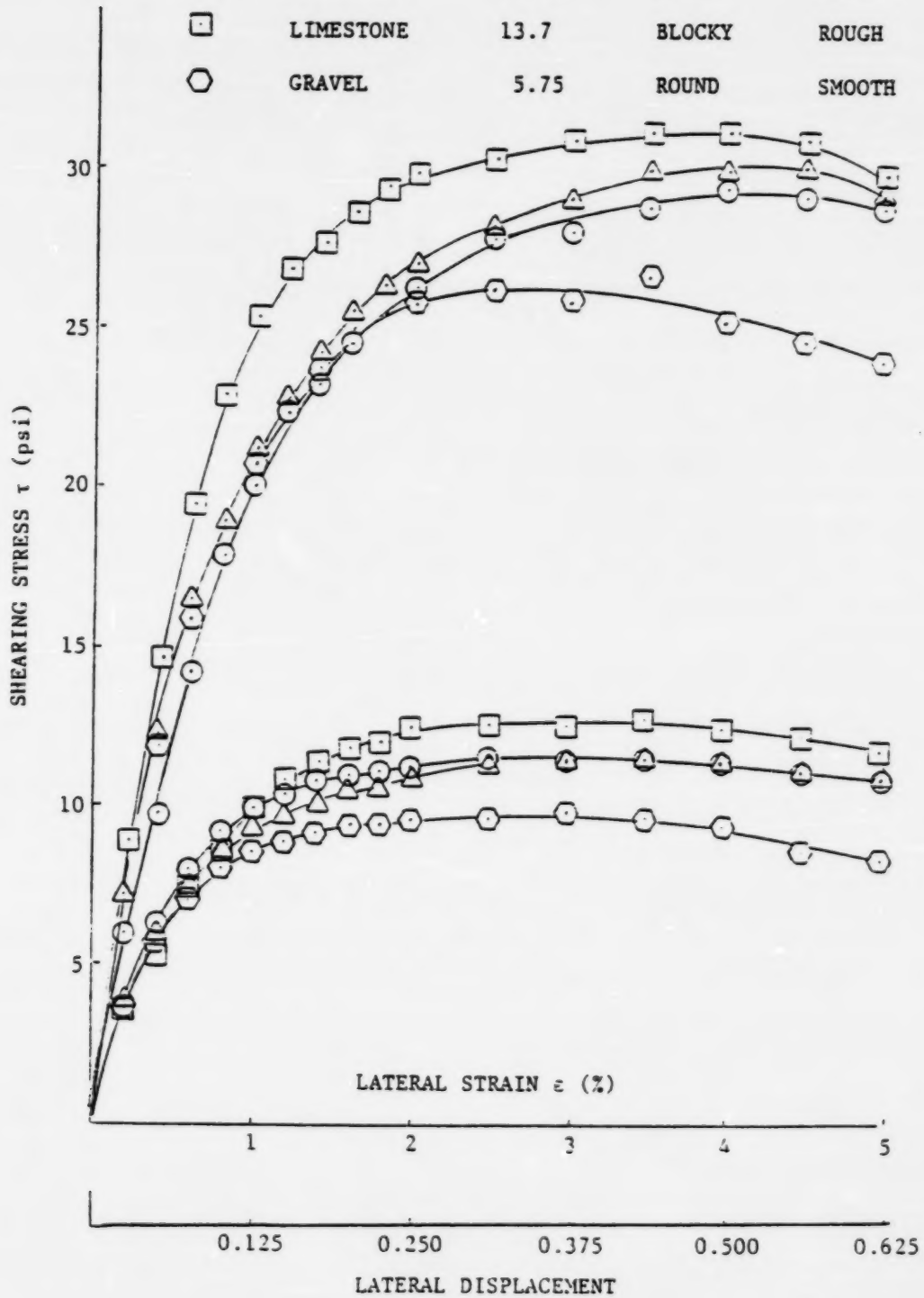

EXHIBIT NO. 11

In the vibrated compaction mode at 1% and 2% strain, the blocky rough textured limestone had the highest shear strength of the four samples.

The magnitude of the Particle Shape Index test reflected the shape and texture of the particles: rounded particles produced a low value, flat particles produced a high value. Surface roughness or texture had an effect on the value, a glossy smooth surface tended to produce a low value.

Flakiness and Particle Shape Index tests correlated well. In Table No. 13 and Exhibit No. 12 a correlation is seen. The Particle Shape number is approximately 1/2 of the Flakiness Index number.

TABLE NO. 13

PARTICLE SHAPE INDEX vs FLAKINESS INDEX

No.	Aggregate	Shape	Texture	Particle Shape	Flakiness Index
1	Slag	Rounded	Smooth	7.23	14.2
2	Trap Rock	Flat	Rough	16.83	38.0
3	Limestone	Blocky	Rough	13.7	25.1
4	Gravel	Round	Smooth	5.75	10.2

FLAKINESS INDEX VS. PARTICLE SHAPE INDEX

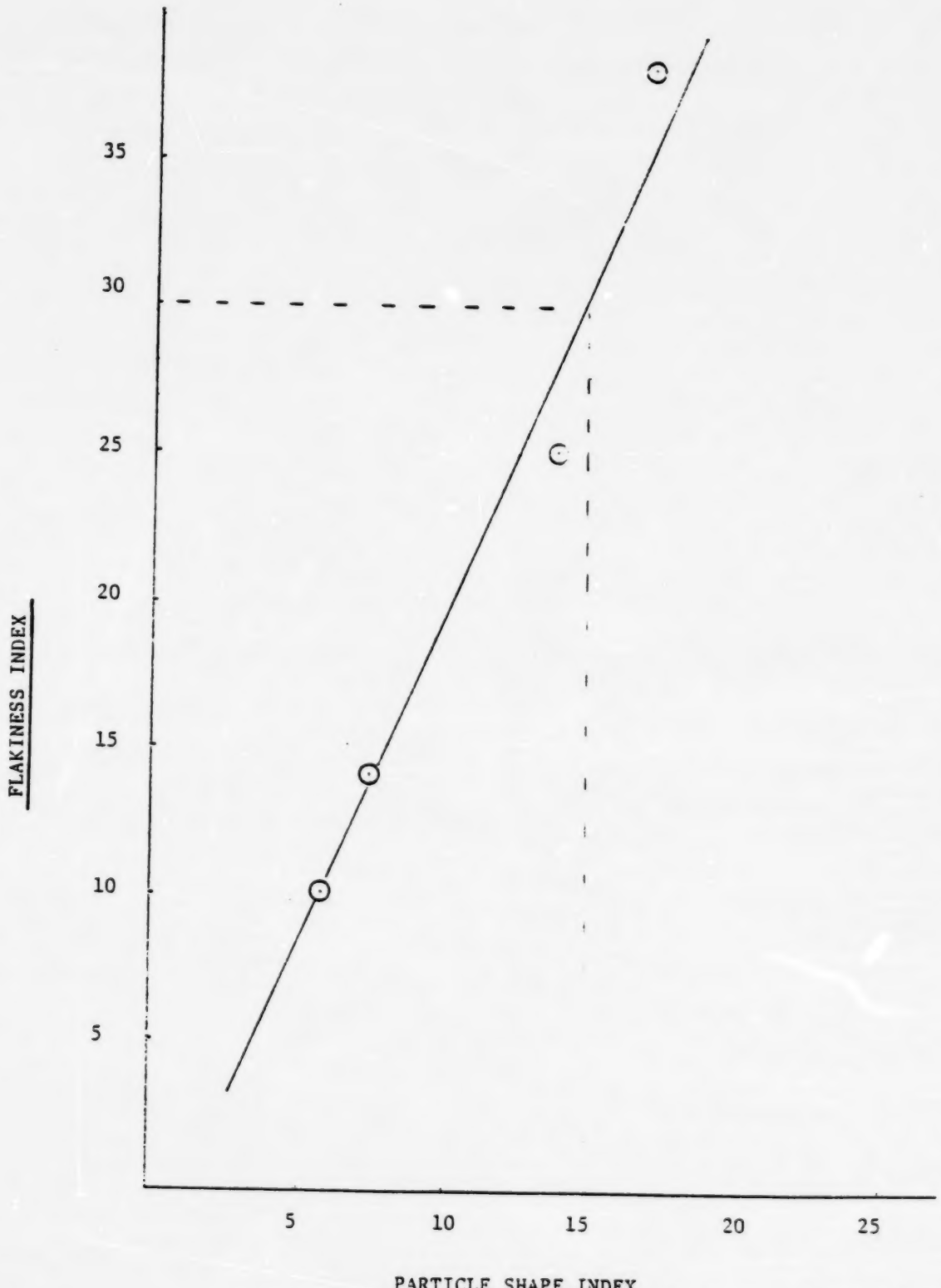

EXHIBIT NO. 12

7. CONCLUSIONS

7.1 Hudson's Gradation Modulus A Index test defines a gradation with one number and a specification range with two numbers and is very useful in comparing gradations and ballast specifications.

7.2 A broader-ranged ballast produced an increase in shear strength and density.

7.3 Compaction increased shear strength.

7.4 When a light compacted effort was used, a rounded gravel aggregate compacted well and produced a higher resistance to shear than aggregates that were more difficult to compact.

7.5 Aggregates with good interlocking features compacted well with heavy compactive efforts.

7.6 The Particle Shape Index correlated well with the Flakiness Index, and was approximately 1/2 of the Flakiness Index number.

8. RECOMMENDATIONS

8.1 The Hudson's Gradation Modulus A Index test should be used as an aid in the application of specifications to the production of ballast aggregates.

8.2 It is clear that a broader ranged ballast increased density and shear strength in the laboratory. Field tests should be done to evaluate whether a broader graded ballast will aid in keeping the track in better line and level.

8.3 Since an increase in compaction increased ballast shear strength, the use of compaction equipment should be further evaluated and optimized.

8.4 A broader ranged ballast should be used to obtain a higher density and a greater resistance to shear deformation.